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(पहला पुनरीक्षण)

Indian Standard

COAL (CHAR) REACTIVITY FOR DIRECT REDUCTION PROCESS — METHOD OF DETERMINATION

(First Revision)

UDC 669·162-16 : 669·162·263·234 : 534·878

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BUREAU OF INDIAN STANDARDS
MANAK BHAVAN, 9 BAHADUR SHAH ZAFAR MARG
NEW DELHI 110002

December 1994 **Price Group 5**

Sponge Iron and Smelting Reduction Sectional Committee, MTD 30

FOREWORD

This Indian Standard (First Revision) was adopted by the Bureau of Indian Standards, after the draft finalized by the Sponge Iron and Smelting Reduction Sectional Committee had been approved by the Metallurgical Engineering Division Council.

This standard was first published in 1987. The major modification in this revision is the change in the range measurement. Earlier methods covered in this standard were based on the gas-diffusion control range and would not have differentiated between coals of higher reactivities. The parameters selected in this revision, would be able to evaluate intrinsic chemical kinetics. In addition, Method 'C' measures the instantaneous reactivity, whereas all other methods measure reactivities which are average over a period of time.

Quality of raw materials plays a significant role in production of sponge iron by direct reduction processes. With coal based direct reduction, the characteristics of coal (char) directly influences the direct reduction and one of the important properties of coal as the reductant is its reactivity, that is, its ability to react with carbon dioxide and generate carbon monoxide. This standard outlines four methods for determining reactivity of coal, based on procedures being followed. Two of these are based on the principle of loss in weight during reaction and the other two are based on the principle of evolved gas analysis.

The term 'reactivity of coal' refers to the ability of carbon in the char prepared from coal to react with oxidising gases to form carbon monoxide. Depending on the gas (whether oxygen, carbon-dioxide or water vapour), the common terms are oxy, carboxy or hydroxy reactivities of coal. The term relevant for direct reduction processes is the carboxy reactivity and in this standard the term 'Reactivity of Coal' has been used to indicate the carboxy reactivity of the carbon in char made from that coal. This, in effect, means the extent of progress of the following reaction under specified conditions:

$$CO_2 + C = 2CO$$

In reporting the result of a test or analysis made in accordance with this standard, if the final value observed or calculated, is to be rounded off, it shall be done in accordance with IS 2 : 1960 'Rules for rounding off numerical values (*revised*)'.

AMENDMENT NO. 1 AUGUST 2010
TO
IS 12381 : 1994 COAL (CHAR) REACTIVITY FOR DIRECT REDUCTION PROCESS — METHOD OF DETERMINATION

(First Revision)

(*Page* 2, *clause* **6.1**) — Substitute the following for the existing matter:

‘When sample weight is 5 g and carbon dioxide gas is passed at the rate of 50 c.c./min for 120 minutes then:

$$\text{‘Reactivity} = \frac{W \times 44\,800 \times (1\,050 + 273)}{12 \times 273 \times 120 \times 60 \times 5 \times C_{\text{fix}}}$$

$$= \frac{2.5128 \times W}{5 \times C_{\text{fix}}} \text{ c.c./g-sec’}$$

where

C_{fix} = fraction of the Fixed Carbon present in Char before reaction, and

W = weight loss.’

(*Page* 3, *clause* **6.4**) — Substitute the following for the existing matter:

‘For the purpose of this test the following conditions shall be maintained:

a)	Temperature	:	1 050 ± 5°C
b)	Test duration	:	120 minutes
c)	Gas composition	:	Pure and dry CO_2 gas
d)	Gas flow rate	:	50 c.c./min’

(*Page* 3, *clause* **6.6**, *line* 8) — Substitute ‘1 050 ± 5^{o}C’ *for* ‘1 000 ± 5^{o}C’.

(*Page* 3, *clause* **6.6**, *line* 9 *and* 10) — Substitute ‘50 c.c./min for 120 minutes’ *for* 100 c.c./min for 25 minutes’ and substitute ‘120 minutes’ *for* ‘25 minutes’.

(*Page* 3, *clause* **6.7**) — Substitute the following for the existing:

‘Reactivity is reported as follows (*see* **6.1**):

$$\text{Reactivity} \quad = \quad \frac{2.5128 \times W}{5 \times C_{\text{fix}}} \ \text{c.c./g-sec'}$$

(MTD 30)

Indian Standard

COAL (CHAR) REACTIVITY FOR DIRECT REDUCTION PROCESS — METHOD OF DETERMINATION

(First Revision)

1 SCOPE

This standard specifies the methods to be followed for determination of reactivity of coal to be used for direct reduction processes.

Reactivity is measured by reacting the charred coal with carbon dioxide at high temperatures (950 - 1 000°C) and measuring the extent of conversion to carbon monoxide.

2 REFERENCE

The Indian Standard IS 1350 (Part 1) : 1984 'Methods of test for coal and coke : Part 1 Proximate analysis (*second revision*)' is a necessary adjunct to this standard.

3 NUMBER OF TESTS

At first, two sets of tests shall be conducted and if they vary by more than 5 percent, subsequent test(s) shall be conducted till this condition is satisfied for any two tests.

4 PREPARATION OF SAMPLE

Any method of charring which ensures conversion of coal to char without oxidation and retention of not more than 2 percent volatile matter may be adopted.

4.1 Before measurement of reactivity, coal is required to be converted into char. This may be done by the method adopted for the determination of volatile matter in IS 1350 (Part 1) : 1984. But very often this method cannot give as much quantity of char as is required for the reactivity test; and taking larger quantity of coal often leads to larger retention of volatile matter than the permissible limit. Exposure to higher temperatures affect reactivity value and longer times of devolatilization would lead to chances of oxidation which may again alter reactivity characteristics.

4.2 Although, any method of preparation of char sample which gives retained volatile matter less than 2 percent without oxidation, is acceptable, the following method of sample preparation is recommended.

4.3 Adequate quantity of coal is crushed to 1 to 3 mm size by manual crushing. Fines are removed by screening and sample is taken in a container made of stainless steel or any other heat and reaction resistant material shown in Fig. 6. (*see* page 7). Dimensions may be altered as per convenience, taking care that the container can be kept well within the uniform temperature zone of the furnace. With the closed container in position inside the furnace (as shown in Fig. 6), nitrogen or any other inert gas (for example, argon) is passed which is strictly free of any oxidizing gas such as O_2, CO_2, H_2O, etc. Gas flow rate is maintained at about 10 litres/hour or any rate which ensures prevention of ingress of diffusion of atmospheric oxygen. The furnace temperature is gradually raised to 950 ± 5°C and is maintained there for about 3 hours and thereafter the sample is cooled to below 200°C under the protection of flowing gas. After cooling, the sample is taken out and crushed gently and carefully with a hand mortar to obtain the desired size range.

5 LOSS IN WEIGHT METHOD, METHOD 'A'

5.1 Principles of Method

One simple way of finding out reactivity would be to find out the average rate of loss of weight of char sample. It has been found that this rate varies markedly with the extent of reaction. Since the use of coal for direct reduction is mostly in rotary kiln, the standard laboratory test procedure should simulate conditions in a rotary kiln direct reduction plant. In most such plants, 60-75 percent of the fixed carbon of coal charged gets reacted in the kiln and balance 25 - 40 percent comes out with the product as protective char. Throwing of coal from discharge end of the rotary kiln has become a standard practice which makes some fresh char available in the reduction zone. This means that final stage of reduction is helped by the fresh char which is generally much more reactive than the already reacted char existing in the bed. This makes reactivity of the less reacted char more important. Laboratory test should therefore ensure that not more than 60% of the carbon in char gets reacted during the period of determination. In a 200 g char sample, at least 100 g, fixed carbon is expected and if this converts the entire quantity of carbon dioxide flowing over it at the rate of 6 litres/min for 20 minutes, about 59 g of carbon should be consumed.

Let the weight loss during experiment be 'W' g. Therefore carbon monoxide formed is $W \times 22$, 400 × 2/12 c.c. at N.T.P. or $W \times 44,800 \times (t + 273)/(12 \times 273)$ c.c. at the reaction temperature, where 't' is the reaction temperature in degrees celsius. It is customary to express reactivity in terms of volume rate of carbon monoxide evolution at the temperature of reaction per unit average weight of carbon present in the sample. Thus Reactivity = $W \times 44,800 \times (t + 273) / \{12 \times 273 \times Z \times (C_{\text{fix}} \times W_0 - W/2)\}$

where

C_{fix} = fraction of the fixed carbon in the char sample before reaction;

W_0 = weight of char sample before reaction (200 g in this case); and

Z = time of passage of carbon dioxide gas (i.e. time of reaction, 20 minutes in this case).

Substituting values for W_0 and Z we get

Reactivity = $14.51 \times W/(200 \times C_{\text{fix}} - W/2)$ c.c./g-sec.

5.2 Outline of the Method

Reactivity is determined as the volume rate of evolution of carbon monoxide through gasification of carbon by carbon dioxide per unit carbon at a specified temperature.

5.3 Sample

For the purpose of this test a sample of 200 g shall be taken having a size range of 1 to 2 mm.

5.4 Test Conditions

For the purpose of this test the following conditions shall be maintained:

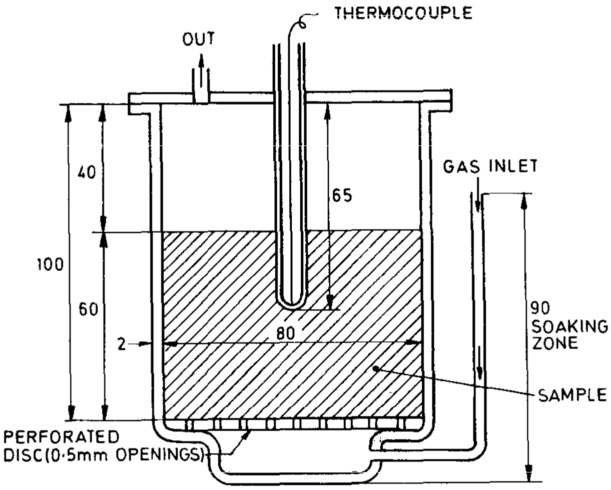
a)	Temperature	1 000 ± 5°C
b)	Test duration	20 minutes
c)	Gas composition	Pure and dry CO_2 gas
d)	Gas flow rate	6 litres/min

5.5 Test Apparatus

The electric furnace shall have a minimum depth of 90 mm and shall be capable of getting a temperature of 1 000 ± 5°C. The apparatus made of stainless or heat resistant steel is shown in Fig. 1A and its location in the furnace is indicated in Fig. 1B.

5.6 Procedure

The sample is first dried at 150°C for two hours and then inserted in the reaction tube [a parallel sample is taken out and the fixed carbon determined by the method given in IS 1350 (Part 1) : 1984]. The reaction tube is covered with lid and then heated to 1 000 ± 5°C in a current of nitrogen gas (1 litre/min). The sample temperature is monitored by a sheathed thermocouple whose tip is inserted into the sample.



All dimensions in millimetres.

FIG. 1A DIMENSIONS OF REACTION TUBE, METHOD A

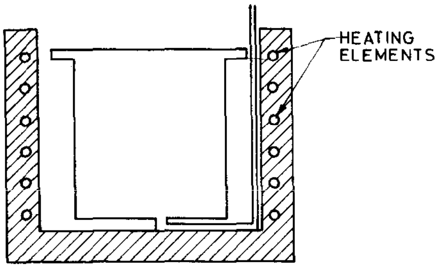


FIG. 1B REACTIVITY APPARATUS

Carbon dioxide gas from a cylinder, dried in a tower of magnesium perchlorate, is passed through the reaction tube at the rate of 6 litres per minute for twenty minutes. After that, the sample is cooled to room temperature in nitrogen atmosphere, the flow rate of which is same as during heating (namely, 1 litre/min).

5.7 Test Report

Reactivity is reported as follows (*see* **5.1**)

Reactivity = $14.51 \times W/(200 \times C_{\text{fix}} - W/2)$ c.c./g-sec.

6 LOSS IN WEIGHT METHOD, METHOD 'B'

6.1 Principle of Method

When sample weight is 5 g and carbon dioxide gas is passed at the rate of 100 c.c./min for 25 minutes then:

$$\text{Reactivity} = W \times 44,800 \times 1\,273/\{12 \times 273 \times (5 \times C_{\text{fix}} - W/2) \times 25 \times 60\} \text{ c.c./g-sec}$$
$$= 11.61 \times W/(5 \times C_{\text{fix}} - W/2) \text{ c.c./g-sec}$$

6.2 Outline of the Method

Reactivity is determined as the volume rate of evolution of carbon monoxide through gasification of carbon by carbon dioxide per unit carbon at a specified temperature.

6.3 Sample

For the purpose of this test a sample of 5 g shall be taken having a size range of 0.5 to 1.0 mm.

6.4 Test Conditions

For the purpose of this test the following conditions shall be maintained:

a)	Temperature	1 000 ± 5°C
b)	Test duration	25 minutes
c)	Gas composition	Pure and dry CO_2 gas
d)	Gas flow rate	100 c.c./min

6.5 Test Apparatus

The set up for reactivity determination is represented in Fig. 2. The reaction tube (Quartz Tube) is made of transparent silica and is approximately 25 mm in inside diameter. In addition, a suitable arrangement for passing nitrogen is also required.

6.6 Procedure

A representative sample of 5 g of 0.5 to 1.0 mm size is taken in the quartz tube, sealing both ends of sample by either quartz wool or a 200 mesh circular screen made of stainless steel. The tube is so kept in the furnace that the sample is in the uniform temperature zone. Nitrogen gas is passed at the rate of 50 c.c. per minute and the test sample is preheated to 1 000 ± 5°C. After the temperature has stabilized carbon dioxide gas is passed at the rate of 100 c.c./min for 25 minutes. After completion of 25 minutes, carbon dioxide flow is stopped and instead nitrogen gas is passed at the earlier rate of 50 c.c./min until the temperature of reacted sample is brought to below 150°C. Care should be taken while passing nitrogen that no ash particle is blown off from the quartz tube. The remaining sample is then weighed after transferring very carefully from the quartz to a suitable container.

6.7 Test Report

Reactivity is reported as follows (*see* **6.1**)

Reactivity = $11.61 \times W/(5 \times C_{fix} - W/2)$ c.c./g-sec

7 GAS ANALYSIS METHOD, METHOD 'C'

7.1 Principle of Method

7.1.1 Extent of gasification can also be monitored by analysing the evolved gases and this method is free from errors arising out of dropping or blowing off of ash particles. For intimate contact carbon dioxide should be passed through a column of char. Since carbon monoxide is much lighter than carbon dioxide, channeling in the column is expected if gases pass up through the column. When gases are passed down the column all the problems mentioned above are overcome, but lower layers of char encounter gas which are getting progressively enriched by carbon monoxide. To account for this phenomenon the concept of Damkoehler Number has to be incorporated. Annex A lists the values of Damkoehler Number for different percentages of carbon monoxide in the exit gas. Damkoehler Number represents the ratio of the residence time of the gas to the mean life of a reacting species in the gas.

7.1.2 Use of this approach enables to measure reactivity value instantaneously and need to average out over a period is obviated.

It is customary to measure reactivity at a point when 0.5 g of carbon has been gasified from a sample of 5 g. To determine the instant (i. e. the time) when gasification of 0.5 g of carbon is completed, a graph is drawn at the end of the experiment, between instantaneous gasification rate of carbon (g.c/h) and time. A sample plot is given in Fig. 5. (*see* page 7). The instantaneous gasification rate can be shown to be related to the percent carbon monoxide in the exit gas by the following relationship.

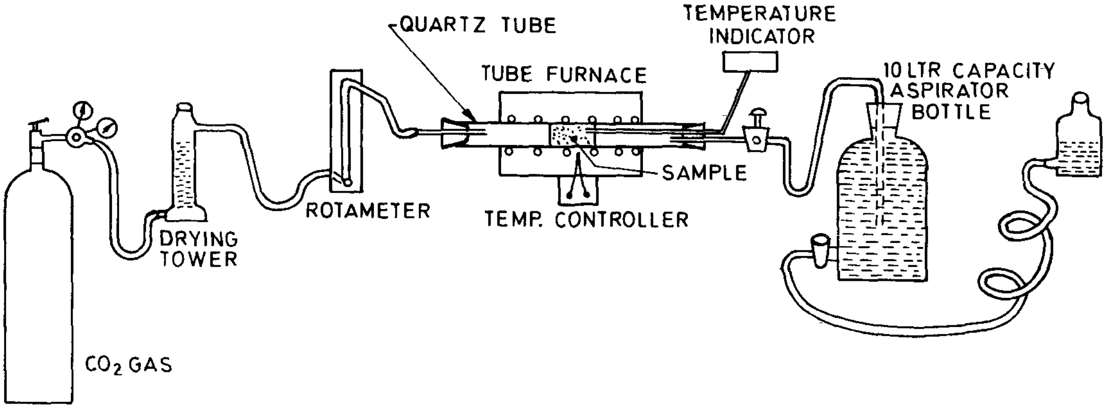


FIG. 2 APPARATUS FOR DETERMINATION OF REACTIVITY OF COAL, METHOD B

Instantneous gasification rate

$$= V \times (273/t_0 + 273) \times (12/22.4)/(200/\text{Vol\% CO-1})\ \text{g.c/h}$$

where V = volume flow rate of CO_2 in litres/hour

t_0 = room temperature in degrees Celsius

In this method (Method C), the expression reduces to

$$= \text{Vol\% CO}/(45.27 - 0.228 \times \text{Vol\% CO})\ \text{g.c/h.}$$

For simplification, the values have been Tabulated in Annex A.

7.1.3 After plotting the graph, the area under the curve is counted to locate the instant (i.e. the time) when the integrated area equals 0.5 g of carbon removed.

7.1.4 The reactivity may be defined as the instantaneous rate of evolution of carbon monoxide per unit carbon present. The carbon remaining at that instant (when 0.5 g carbon is removed) is 0.5 g less than that present in the beginning of the experiment and is therefore equal to $(W \times C_{fix} - 0.5)$ g.

It can be shown

that Reactivity $= [V \times (t + 273)/(t_0 + 273)/3.6] \times Da/(W \times C_{fix} - 0.5)$

Where Da is the Damkoehler Number, which is given by

$$Da = 2 \times \ln [(200 - \text{Vol\% CO})/(200 - 2 \times \text{Vol \% CO})] - \text{Vol\% CO}/(200 - \text{Vol\% CO})$$

In the present case

$$\text{Reactivity} = (V \times 1\,000/3\,600) \times (1\,273/298) \times Da/(5 \times C_{fix} - 0.5)$$

$$= 10.68 \times Da/(5 \times C_{fix} - 0.5)$$

Room temperature has been assumed to be 25°C. For matching results when conducted at a different room temperature, it is recommended that gas flow may be adjusted using Gas Law to obtain the same expression for Reactivity.

7.2 Outline of the Method

Reactivity is determined as the instantaneous volume rate of evolution of carbon monoxide through gasification of carbon by carbon dioxide per unit carbon at a specified temperature.

7.3 Sample

For the purpose of this test a sample of 5 g shall be taken having a size range of 0.5 to 1 mm.

7.4 Test Conditions

For the purpose of this test the following conditions shall be maintained:

a)	Temperature	1 000 ± 5°C
b)	Test duration	30 minutes approx
c)	Gas composition	Pure and dry CO_2 gas
d)	Gas flow rate	9 l/h

7.5 Test Apparatus

The set up for reactivity determination is represented in Fig. 3. This essentially consists of an electrically heated tubular furnace (A), a quartz reactor tube of approximately 15 mm internal diameter (B), an infra red detector for continuous measurement of carbon monoxide in the exit gas (C), and a recorder for recording temperature and %CO in the exit gas (D). The furnace should be controlled preferably by a PID controller with an accuracy of ±5°C. The furnace tube should preferably be 200 mm long and should be about 25 mm in diameter.

7.6 Procedure

7.6.1 The reaction tube is constricted in the lower end as shown in Fig. 3. A plug of quartz wool is placed above the constriction and is carefully pressed in taking care not to block gas passage.

7.6.2 For measurement of sample temperature, placement of thermocouple tip in the uniform temperature zone of the sample has to be assured. For this purpose, thermocouple should be adjusted using a locking ring.

7.6.3 5 g of char sample having a grain size of 0.5 to 1.0 mm is filled in the reaction tube and the upper glass tube with the adjusted thermocouple is placed in position. The tip of the thermocouple should be well within the sample and care should be taken that it is not in contact with the side of the reaction tube.

7.6.4 Gentle tapping should stabilise the filling. The depth of the bed should be 40 to 90 mm depending on the bulk density of the char. The reaction tube is then mounted on the support outside the furnace and is connected to carbon dioxide cylinder as indicated in Fig. 3. Gas is allowed to pass for about 15 minutes (Scavenging). Simultaneously, furnace is brought to the set temperature of 1 000 ± 5°C. Once scavenging is complete, the reaction tube is removed from the conical ground glass joint III, inserted into the furnace and is connected to a similar ground glass joint IV as indicated in Fig. 3. The thermocouple (a) is connected to the printer for continuous sample temperature record.

7.6.5 Printer is started and carbon dioxide gas is passed at the rate of 9 litres per hour (at 25°C) with both three-way cocks '*X*' and '*Y*' having been set to 'measurement'. After measurements are complete, gas flow is stopped, reaction tube is taken out of the furnace and placed back on the support.

7.7 Test Report

Reactivity is reported as follows (*see* **7.1**)

Reactivity $= 10.68 \times Da/(5 \times C_{fix} - 0.5)$ c.c./g. sec

NOTE — This method may be used as referee method and should not be used for routine testing.

8 GAS ANALYSIS METHOD, METHOD 'D'

8.1 Principle of Method

Under given conditions reactivity can be measured by finding out that flow rate of carbon dioxide which allows 15 percent conversion from carbon dioxide to carbon monoxide (this corresponds to 26 percent carbon monoxide or 74 percent carbon dioxide in the exit gas). This is a simple index, but different from earlier reactivity concepts and therefore this would be referred to here as 'Reactivity Index' (*U*) expressed in c.c./minute carbon dioxide. It is, therefore, Volume of carbon monoxide evolved

$$= U \times 0.15 \times 2 \times (t + 273)/[(t_0 + 273) \times 60] \text{ c.c./sec.}$$

This divided by the weight of carbon in the char would give reactivity value which can be compared with those obtained from other methods. However, they are still not strictly comparable if temperatures of measurement are not same. To compare results obtained at different temperatures, the concept of 'Reactivity Factor, H' may be introduced as follows:

Assuming the gasification reaction follows Arrhenius Equation with activation energy of 86, 000 cal./g. mole

$$\text{Gasification rate} = HM\,(n - n_0)\ \text{exponential}(-86\,000/RT)$$

where

H = reactivity Factor of char, c.c./g.-sec

M = amount of carbon per unit volume of charge bed, g./c.c.

n = concentration of reacting carbon dioxide gas, g.mole/c.c.

= 1/22, 400 g.mole/c.c. at NTP in the present case (pure carbon dioxide is passed)

= 1/100, 349 g.mole/c.c. at reaction temp. (950°C)

n_0 = equilibrium concentration of carbon dioxide at boundary layer

= 0.015/100, 349 g.mole/c.c. at 950°C

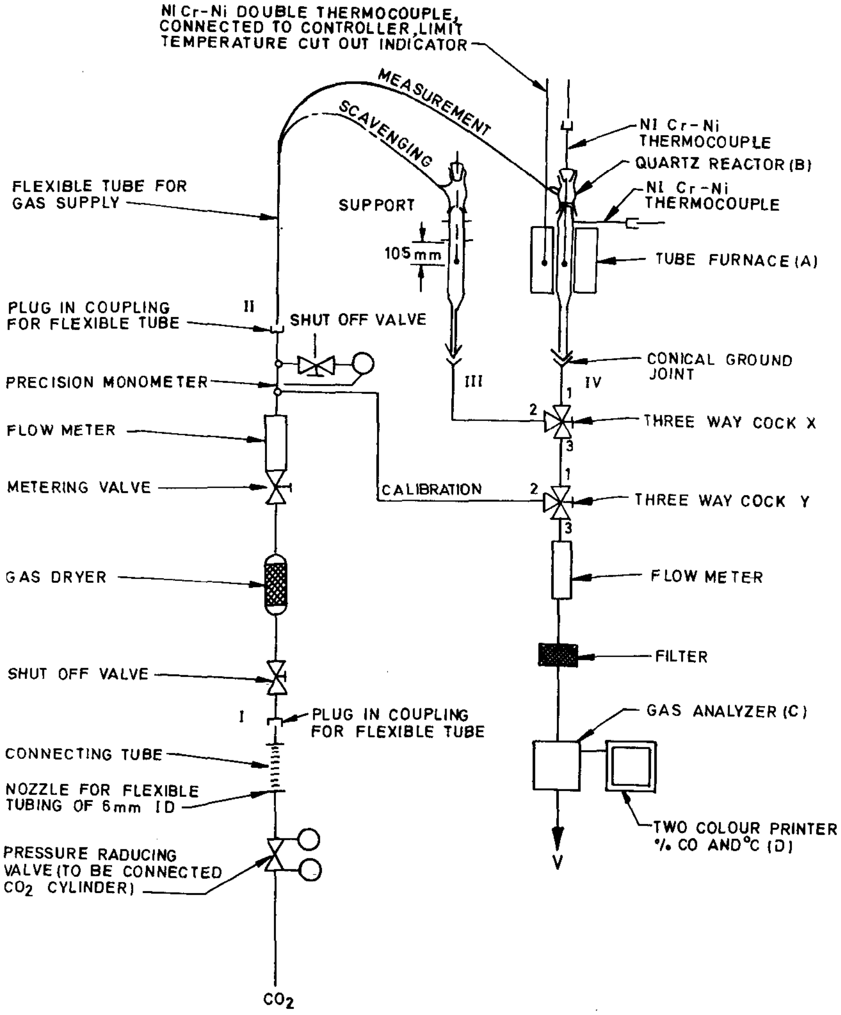


FIG. 3 GAS FLOW DIAGRAM OF THE APPARATUS FOR DETERMINATION OF THE REACTIVITY OF CHAR, METHOD C

Let U_c be the gasification rate at the temperature of reaction.

$$U_c = U \times 0.15 \times 2 \times (t + 273) \times [(t_0 + 273) \times 60]$$

$$\text{Reactivity} = \text{Gasification rate/carbon in the bed} = U_c/(M \times \text{Bed volume})$$

now,

$$H \times (n - n_0) \text{ exponential } (-86\,000/RT) = \text{Reactivity} \times \text{Bed volume}$$

Therefore,

$$H = \text{Reactivity} \times \text{Bed volume}/[(n - n_0) \text{ exponential } (-86\,000/RT)]$$

If sample weight and sample bed volume are known, Reactivity Factor (H) may be calculated from the Reactivity and Reactivity Index values obtained from different methods for true comparison of coal property.

8.2 Outline of the Method

The rate of reaction between carbon dioxide and carbon is dependent on the rate of flow of carbon dioxide through the char (produced from coal) bed. Under standard conditions (temperature, size of char, height of char bed, etc), the reactivity index of char may be measured by the rate of passage of carbon dioxide through the char bed for a fixed degree of conversion of carbon dioxide to carbon monoxide (*see* **8.1**).

8.3 Sample

For the purpose of this test a sample shall be taken having a size range of 0.6 to 1.2 mm. The quantity of sample should be sufficient so that the quartz reaction tube of about 15 mm dia could be filled to a height of 100 mm.

8.4 Test Conditions

For the purpose of this test the following conditions shall be maintained:

a) Temperature	950 ± 5°C
b) Test duration	10 minutes each for flow rates of CO_2 of 100, 200, 300, 400 and 500 c.c. per minute
c) Gas composition	Pure and dry CO_2 gas

8.5 Test Apparatus

The set up for reactivity determination is represented in Fig. 4. This essentially consists of a carbon dioixde gas cylinder (A), the outlet of which is connected

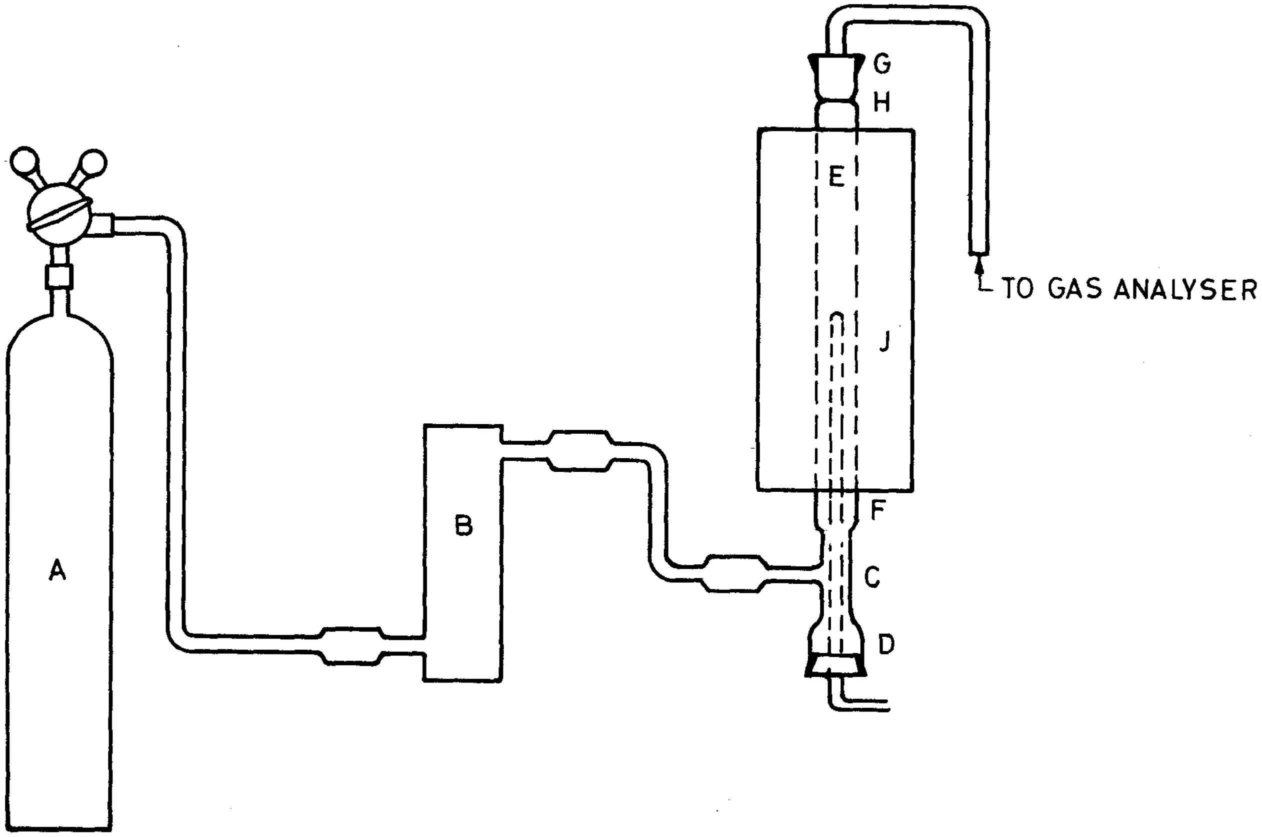


FIG. 4 ASSEMBLY FOR REACTIVITY APPARATUS, METHOD D

to a rotameter (B), which in turn is connected to the quartz reaction tube (E) of approximately 15 mm internal diameter. The tube is fitted at the inlet end with a glass inspection head (C) containing a single hole rubber bung for the insertion of a thermocouple sheath (D). The exit end of the reaction tube is fitted with another glass tube (H) containing an asbestos bung (G) carrying a tube for the exit gases. The exit gases are led either to an infra red detector for continuous measurement of carbon dioxide, or to an Orsat apparatus.

8.6 Procedure

The inlet end of the reaction tube is packed with a 170 mm column of firebrick chips (1.7 to 2.8 mm in size) after which the sample is placed (100 mm column). The exit end of the reaction tube is packed with porcelain rods 150 mm in length and 5 mm in dia. The reaction tube is held vertically inside a tubular furnace (J) as shown in Fig. 4. The furnace should be capable of attaining a uniform temperature of 950 ± 5°C which could be measured by Pt-PtRh thermocouple.

The temperature of the tubular furnace is raised to 950 ± 5°C and maintained at the temperature during the course of the experiment. Pure nitrogen gas from a cylinder is passed through the reaction tube. After the conditions are stabilized, nitrogen is flushed off the system by passing carbon dioxide and five runs are taken with varied rate of flow of carbon dioxide and exit gas for each run is analysed for carbon dioxide separately.

8.7 Test Report

Reactivity Index is read from the graph between flow rate and percent carbon dioxide in the exit gas. It is the flow rate of carbon dioxide at which there is 74 percent carbon dioxide in the exit gas (*see* **8.1**).

NOTE — This method may be used as referee method and should not be used for routine testing.

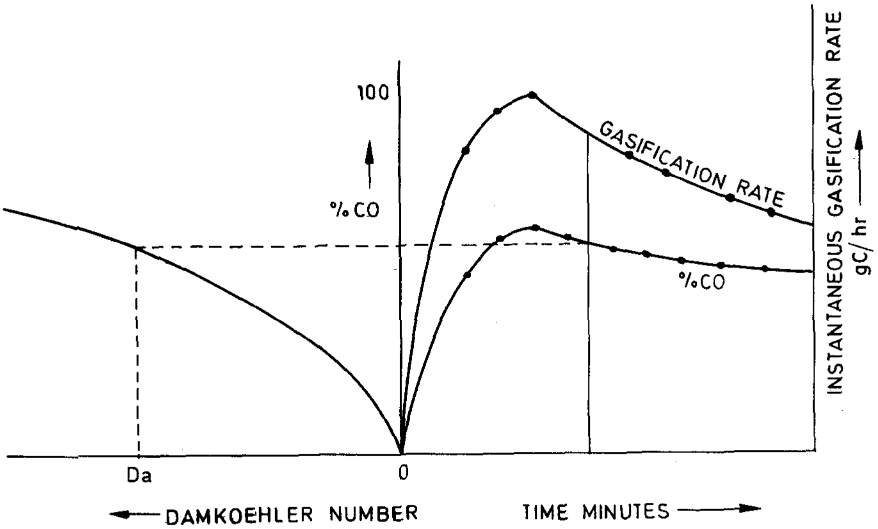


FIG. 5 DETERMINATION OF DAMKOEHLER NUMBER (METHOD C)

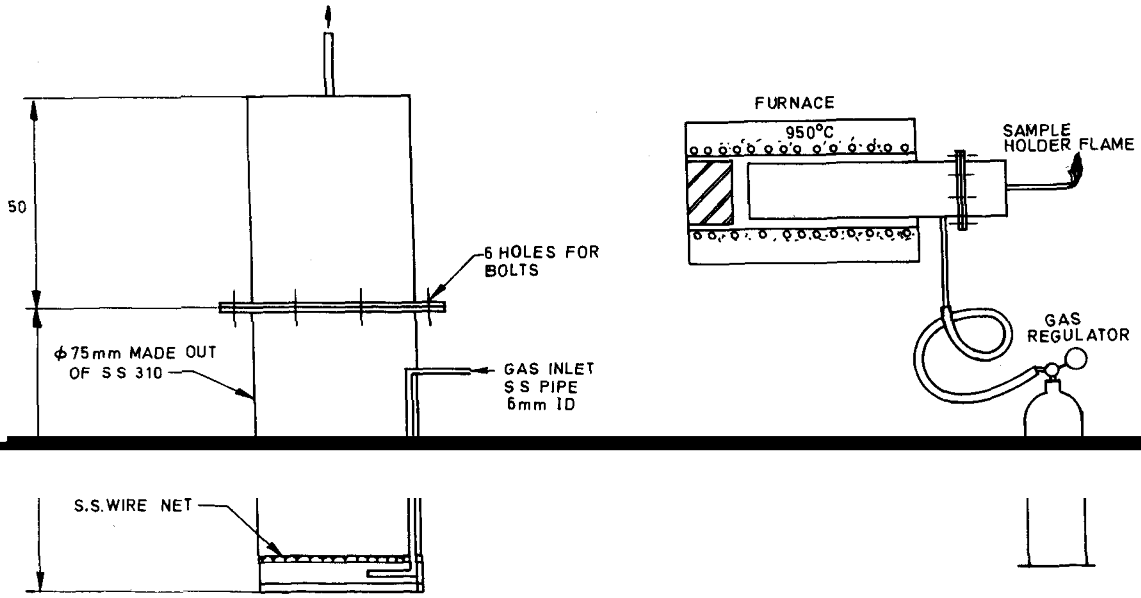


FIG. 6 APPARATUS FOR PREPARATION OF SAMPLE

ANNEX A

(*Clauses* 7.1.1 *and* 7.1.2)

VALUES OF DAMKOEHLER NUMBER FOR DIFFERENT PERCENTAGES OF CARBON MONOXIDE

Vol % CO	Instantaneous Gasification Rate (g.c/h)	Damkoehler Number
0.5	0.011	0.003
1	0.022	0.005
1.5	0.033	0.008
2	0.045	0.010
2.5	0.056	0.013
3	0.067	0.015
3.5	0.079	0.018
4	0.090	0.021
4.5	0.102	0.024
5	0.113	0.026
5.5	0.125	0.029
6	0.137	0.032
6.5	0.148	0.035
7	0.160	0.038
7.5	0.172	0.041
8	0.184	0.043
8.5	0.196	0.046
9	0.208	0.049
9.5	0.220	0.052
10	0.233	0.056
10.5	0.245	0.059
11	0.257	0.062
11.5	0.270	0.065
12	0.282	0.068
12.5	0.295	0.071
13	0.307	0.075
13.5	0.320	0.078
14	0.333	0.081
14.5	0.346	0.085
15	0.358	0.088
15.5	0.371	0.091
16	0.384	0.095
16.5	0.398	0.099
17	0.411	0.102
17.5	0.424	0.106
18	0.437	0.109
18.5	0.451	0.113
19	0.464	0.117
19.5	0.478	0.121
20	0.491	0.124
20.5	0.505	0.128
21	0.519	0.132
21.5	0.533	0.136
22	0.547	0.140
22.5	0.561	0.144
23	0.575	0.148
23.5	0.589	0.153
24	0.603	0.157
24.5	0.617	0.161
25	0.632	0.165
25.5	0.646	0.170
26	0.661	0.174
26.5	0.676	0.179
27	0.690	0.183
27.5	0.705	0.188
28	0.720	0.193
28.5	0.735	0.197
29	0.750	0.202
29.5	0.765	0.207
30	0.781	0.212
30.5	0.796	0.217
31	0.811	0.222
31.5	0.827	0.227
32	0.843	0.232
32.5	0.858	0.237
33	0.874	0.243
33.5	0.890	0.248
34	0.906	0.254
34.5	0.922	0.259
35	0.939	0.265
35.5	0.955	0.270
36	0.971	0.276
36.5	0.988	0.282
37	1.004	0.288
37.5	1.021	0.294
38	1.038	0.300
38.5	1.055	0.306
39	1.072	0.313
39.5	1.089	0.319
40	1.106	0.325
40.5	1.124	0.332
41	1.141	0.339
41.5	1.159	0.345
42	1.177	0.352
42.5	1.194	0.359
43	1.212	0.366
43.5	1.230	0.373
44	1.249	0.381
44.5	1.267	0.388
45	1.285	0.396
45.5	1.304	0.403
46	1.322	0.411
46.5	1.341	0.419
47	1.360	0.427
47.5	1.379	0.435
48	1.398	0.443
48.5	1.417	0.452
49	1.437	0.460
49.5	1.456	0.469
50	1.476	0.478
50.5	1.496	0.487
51	1.516	0.496
51.5	1.536	0.505
52	1.556	0.514

Vol % CO	Instantaneous Gasification Rate (g.c/h)	Damkoehler Number
52.5	1.576	0.524
53	1.597	0.534
53.5	1.617	0.544
54	1.638	0.554
54.5	1.659	0.564
55	1.680	0.575
55.5	1.701	0.585
56	1.723	0.596
56.5	1.744	0.607
57	1.766	0.618
57.5	1.788	0.630
58	1.810	0.642
58.5	1.832	0.653
59	1.854	0.666
59.5	1.876	0.678
60	1.899	0.691
60.5	1.922	0.704
61	1.945	0.717
61.5	1.968	0.730
62	1.991	0.744
62.5	2.014	0.758
63	2.038	0.772
63.5	2.062	0.787
64	2.086	0.801
64.5	2.110	0.817
65	2.134	0.832
65.5	2.159	0.848
66	2.183	0.864
66.5	2.208	0.881
67	2.233	0.898
67.5	2.258	0.915
68	2.284	0.933
68.5	2.310	0.951
69	2.335	0.969
69.5	2.361	0.988
70	2.388	1.008
70.5	2.414	1.028
71	2.441	1.048
71.5	2.468	1.069
72	2.495	1.091
72.5	2.522	1.113
73	2.549	1.136
73.5	2.577	1.159
74	2.605	1.183
74.5	2.633	1.207
75	2.662	1.233
75.5	2.690	1.259
76	2.719	1.285
76.5	2.748	1.313
77	2.777	1.341
77.5	2.807	1.370
78	2.837	1.400
78.5	2.867	1.431
79	2.897	1.463
79.5	2.928	1.496
80	2.959	1.531
80.5	2.990	1.566
81	3.021	1.602
81.5	3.053	1.640
82	3.085	1.679
82.5	3.117	1.720
83	3.149	1.762
83.5	3.182	1.806
84	3.215	1.852
84.5	3.248	1.899
85	3.282	1.948
85.5	3.316	2.000
86	3.350	2.054
86.5	3.384	2.110
87	3.419	2.169
87.5	3.454	2.230
88	3.490	2.295
88.5	3.525	2.363
89	3.561	2.435
89.5	3.598	2.511
90	3.635	2.591
90.5	3.672	2.676
91	3.709	2.767
91.5	3.747	2.864
92	3.785	2.967
92.5	3.824	3.078
93	3.862	3.198
93.5	3.902	3.328
94	3.941	3.470
94.5	3.981	3.626
95	4.022	3.798
95.5	4.062	3.990
96	4.103	4.207
96.5	4.145	4.455
97	4.187	4.744
97.5	4.229	5.090
98	4.272	5.517
98.5	4.315	6.072
99	4.359	6.864
99.5	4.403	8.230

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This Indian Standard has been developed from Doc : No. MTD 30 (3783)

Amendments Issued Since Publication

Amend No.	Date of Issue	Text Affected

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Printed at Printrade, New Delhi, India